Soiling of building envelope surfaces and its effect on solar reflectance—Part I: Analysis of roofing product databases

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DISCLAIMER

Abstract

The use of highly reflective "cool" roofing materials can decrease demand for air conditioning, mitigate the urban heat island effect, and potentially slow global warming. However, initially high roof solar reflectance can be degraded by natural soiling and weathering processes. We evaluated solar reflectance losses after three years of natural exposure reported in two separate databases: the Rated Products Directory of the US Cool Roof Rating Council (CRRC) and information reported by manufacturers to the US Environmental Protection Agency (EPA)'s ENERGY STAR® rating program. Many product ratings were culled because they were duplicative (within a database) or not measured. A second, site-resolved version of the CRRC dataset was created by transcribing from paper records the site-specific measurements of aged solar reflectance in Florida, Arizona and Ohio.

Products with high initial solar reflectance tended to lose reflectance, while those with very low initial solar reflectance tended to become more reflective as they aged. Within the site-resolved CRRC database, absolute solar reflectance losses for samples of medium-to-high initial solar reflectance were 2 - 3 times greater in Florida (hot and humid) than in Arizona (hot and dry); losses in Ohio (temperate but polluted) were intermediate. Disaggregating results by product type—factory-applied coating, field-applied coating, metal, modified bitumen, shingle, single-ply membrane and tile—revealed that absolute solar reflectance losses were largest for field-applied coating, modified bitumen and single-ply membrane products, and smallest for factory-applied coating and metal products.

The 2008 Title 24 provisional aged solar reflectance formula overpredicts the measured aged solar reflectance of 0% to 30% of each product type in the culled public CRRC database. The rate of overprediction was greatest for field-applied coating and single-ply membrane products and least for factory-applied coating, shingle, and metal products. New product-specific formulas of the form $\rho'_{\mathrm{a}} = 0.20 + \beta\left(\rho_{\mathrm{i}} - 0.20\right)$ can be used to estimate provisional aged solar reflectance ρ'_{a} from initial solar reflectance ρ_{i} pending measurement of aged solar reflectance. The appropriate value of soiling resistance β varies by product type and is selected to attain some desired overprediction rate for the formula. The correlations for shingle products presented in this paper should not be used to predict aged solar reflectance or estimate provisional aged solar reflectance because the data set is too small and too limited in range of initial solar reflectance.

Introduction

The use of a highly reflective “cool” roof can reduce the annual air conditioning energy use of a typical commercial building by about 20% [1]. Widespread use of reflective roofs can also cool outside air, helping mitigate the urban heat island effect [2] and potentially slowing global warming [3-4]. However, the solar reflectance (fraction of incident sunlight reflected) of an initially reflective building envelope surface is often reduced by soiling and weathering [5]. This study evaluates the extent to which three years of natural aging changes the solar reflectance of roofing products exposed in a variety of U.S. climates.

We examine subsets of the initial and three-year aged (hereafter, simply "aged") measurements of roof solar reflectance reported in each of three databases: an edited version of the public Rated Products Directory published online by the US Cool Roof Rating Council (CRRC) [6]; a site-resolved version of the CRRC database that includes aged measurements made in three specific climates; and an edited version of the ENERGY STAR® Roof Product List of the US Environmental Protection Agency (EPA) [7]. The edits seek to eliminate duplicative values and non-measured results. In the EPA database, aged solar reflectance is provided by the manufacturer, and can be an average of in-situ measurements made on three buildings, aged measurements from one climate zone, or taken from CRRC ratings. The EPA program does not standardize its exposure sites, and requires only that at least one building be located in a U.S. major metropolitan area [8].

The CRRC database was initiated in 2005 and reported aged solar reflectances for 1357 products as of April 2011. The EPA database began in 2002, and contained aged reflectances for 5397 products as of March 2011.

We note two limitations to the CRRC and EPA databases. First, neither includes spectrally resolved reflectance measurements that could help identify soiling agents. Second, the solar reflectance metric used in these databases overestimates the solar reflectance of many spectrally selective materials, such as “cool colored” roofing products [9-10].

This study seeks to

- explore how climate and product type affect loss of solar reflectance;

- relate aged solar reflectance to initial solar reflectance for each product type in the CRRC and EPA databases; and
- provide formulas specific to each product type that can be used to estimate a "provisional" value of aged solar reflectance for a new product while its measured value of aged solar reflectance is pending three years of natural exposure.

Our analysis may help improve the CRRC and EPA roofing product rating systems, which are referenced by major building energy efficiency standards and energy efficiency rebate programs, and will support the development of international roof rating systems. It will also identify those product types whose solar reflectances are most degraded by aging. A better understanding of this effect will help develop a new generation of advanced building envelope materials. These can retain high solar reflectance through improved resistance to soiling and/or incorporation of antimicrobial and self-cleaning functionalities [11-14].

Product types

The CRRC provides the following product type definitions.

Field-applied coating. Applied directly onto the roof surface, either on a new roof assembly or over an existing roof surface.

Factory-applied coating. Applied at the factory prior to distribution. Includes paints applied to metal and glazes applied to tiles.

Metal. Can be shaped to look like shingles, or shakes, or to fit unique curvatures, in addition to a typical "standing seam" configuration. They come in a variety of textures and colors.

Modified bitumen. Asphalt or tar modified with polymer additives, layered with reinforcing materials and topped with a surfacing material.

Shingle, slate, or tile. Pieces that fit together to form a roof. Shingles are typically made of asphalt-soaked fiberglass surfaced with granules of colored crushed rock; tile products are made of clay or concrete, and may be coated. Slate is quarried stone.

Single-ply membrane. Pre-fabricated sheet of rubber polymers, which is laid down in a single layer over a low or steep-sloped roof. There are two main types of single-ply materials: thermosets, including ethylene propylene diene monomer (EPDM) and chlorosulfonated polyethylene synthetic rubber (Hypalon®); and thermoplastics, including thermoplastic polyolefin (TPO) and polyvinyl chloride (PVC).

Other product types not included in the above categories include rubber membrane; stucco; roll roofing; built-up roofing (layers of coated asphalt and insulation applied on site, which can be surfaced with cap sheet); and foam roofing (both field- and factory-applied).

Here we consider seven of these products types: factory-applied coating, field-applied coating, metal, modified bitumen, shingle, single-ply membrane and tile. Table 1 details the CRRC and EPA product type values mapped to each product type used in this study.

Database refinement

Many product ratings reported by the CRRC and EPA public databases were omitted from our analysis because they were duplicative (within a database) or not measured. Here we describe how we refined each database for use in this study. We also describe how we created an additional CRRC database with site-resolved aged reflectance measurements from Florida, Arizona, and Ohio.

Editing the CRRC database

The CRRC's Rated Product Directory was initiated in 2005 and contained aged ratings for 1357 products as of April 2011 (Figure 1a, Table 2). We refer to this raw version of the public CRRC database as CRRC0.

CRRC0 includes repeated and/or non-measured product data that we wish to omit from our analysis. To permit removal of these product data CRRC provided us with an augmented version of CRRC0 further detailing each product. The edited version of CRRC0, referred to here as CRRC1 (Table 2), excludes repeated and/or non-measured data. Repeated data can appear for two reasons. First, some products are listed by resellers that rebrand products of another company, referencing the ratings established by the original manufacturer. Hence, these ratings duplicate those of the original product. Second, many metal and factory-applied coating products are assigned default, rather than measured, values of initial and/or aged solar reflectance via the CRRC's "Color Family" program.

The Color Family program allows manufacturers of factory-applied coating and metal products to establish Color Family groups with assigned default solar reflectance (SR) and thermal emittance (TE) ratings. A Color Family group is created with a "representative element" which must meet or exceed the default SR and TE values of that Color Family group, as well as meet pre-determined colorimetry properties. Representative elements must be aged.

The initial default SR and TE listed for each representative element of a Color Family group is used to represent each element listed in the group. If the measured aged SR of the representative element is less than the default SR (defined by CRRC) of the Color Family group, the aged SR listed for this element will be its measured aged SR; otherwise, it will be the default SR for the group. The same process applies to rating the aged TE of the representative element. "Additional elements" (products that meet requirements of similarity in color and initial SR and TE default values) can then reference the ratings of the Color Family group representative element. Thus, the ratings of each additional element duplicate those of the group's representative element.

The ratings for Color Family group members reported in the CRRC's public directory include conservative default values set by the CRRC, rather than actual measured values of solar reflectance. To avoid including repeated and/or non-measured (default) data in our analysis, the CRRC1 edited database used in our analysis (a) excludes resold products; (b) excludes values for Color Family group additional elements; and (c) reports measured (rather than default) values for Color Family group representative elements. This eliminates 49% of the samples present in the CRRC0 raw database, leaving 662 (Figure 1b, Table 2). CRRC1 was used for analysis in this study when not considering site specific results.

Creating a site-resolved CRRC database

Since the CRRC0 raw database does not report site-specific values of aged solar reflectance, the CRRC and Berkeley Lab transcribed these values from the CRRC's internal paper records in

December 2010. This site-resolved database is referred to as CRRC2 (Table 2) and is now further described.

The CRRC product rating program exposes a total of nine coupons of each product at three different weathering farms for three years. Three coupons are exposed in or near Miami, Florida (FL), which is hot and humid; three near Phoenix, Arizona (AZ), which is hot and dry; and three near Cleveland, Ohio (OH), which is temperate but polluted. Products sold for low-slope roofs (pitch ≤ 2:12, or 9.5°) are tilted 5° from horizontal, while those intended for steep roofs (pitch > 2:12) are tilted 45° from horizontal. All coupons face south. We define a product's aged solar reflectance at site k (FL, OH, or AZ), $\rho_{\mathrm{a},k}$ as the mean aged solar reflectance of the three coupons aged at that site, and define the product's average aged solar reflectance ρ_{a} as the mean of $\rho_{\mathrm{a,FL}}$, $\rho_{\mathrm{a,AZ}}$ and $\rho_{\mathrm{a,OH}}$.

The site-resolved CRRC2 database contains 586 products (Figure 1c, Table 2). We note that the "other" category contains approximately 100 more products in CRRC2 (Figure 1c) than it does in CRRC0 or CRRC1 (Figure 1a, b). These “other” products are discontinued and are archived in the paper records used for CRRC2 but do not exist in CRRC0. Since CRRC0 was used to match product type to product IDs in CRRC2 (we originally transcribed product ID but not product type), product type is unknown for these ~100 “other” products. Thus, they are not used in our site-specific analysis. Like the CRRC1 edited database, the CRRC2 site-resolved database excludes repeated and non-measured results. CRRC2 contains fewer products than CRRC1 (Figure 1, Table 2), mostly because some paper records were missing or overlooked.

Culling the EPA’s public database

The EPA’s Roof Product List was initiated in 2002. The raw EPA database (designated EPA0) contained 5397 aged product ratings as of March 2011 (Table 2). However, most of these aged ratings are for metal or coating products (Figure 2a). In 2009, the EPA adopted a Color Family program similar to that of the CRRC for its Roof Product List. Since we are unable to identify which metal and factory-applied coating products in the EPA database are members of a Color Family, we exclude both product types from our analysis of the EPA database. We randomly selected 243 of the 1987 coating products with aged ratings in EPA0. From these we identified

98 that were determined from product data to be field-applied coatings. Removing all metal and coating products and then restoring these 98 field-applied coating products eliminated 95% of the samples present in EPA0, leaving 263 (Figure 2b, Table 2). We refer to this edited version of the EPA database as EPA1.

Modeling aged solar reflectance

A roofing product must be exposed for three years before its aged solar reflectance ρ_{a} can be measured for inclusion in either the CRRC or EPA directory. A simple linear expression to estimate provisional aged solar reflectance ρ'_{a} from initial solar reflectance ρ_{i} pending measurement of aged solar reflectance is

$$\rho'_{\mathrm{a}} = \alpha + \beta\,(\rho_{\mathrm{i}} - \alpha). \tag{1}$$

The parameter α can be considered the solar reflectance of an opaque soil layer, and the parameter β gauges resistance to soiling (ranging from 0 for no resistance to 1 for complete resistance). For example, if $\beta = 0$, the product becomes fully soiled ($\rho'_{\mathrm{a}} = \alpha$), while if $\beta = 1$, the product does not soil ($\rho'_{\mathrm{a}} = \rho_{\mathrm{i}}$). Solar reflectance will be constant for any value of β if $\rho_{\mathrm{i}} = \alpha$.

This model considers only soiling, and neglects processes such as UV bleaching and volatilization of additives. It also does not consider properties other than initial solar reflectance such as material, roughness or spectral reflectance. Eq. (1) treats soil as an opaque layer that partially covers the product. In the Appendix we present for comparison a model that treats soil as a translucent layer that fully covers the product.

The 2008 "Title 24" California Building Energy Efficiency Standards [15] permit use of this model with $\alpha = 0.20$ and $\beta = 0.70$; that is,

$$\rho'_{\mathrm{a,T24}} \equiv 0.20 + 0.70\,(\rho_{\mathrm{i}} - 0.20). \tag{2}$$

This model was designed to degrade the solar reflectance of a typical white single-ply membrane or white field-applied coating to an aged value of 0.55 from an initial value of 0.70, and to maintain the solar reflectance of a typical dark gray roof at 0.20. It predicts that soiling decreases the solar reflectance of a surface with $\rho_{\mathrm{i}} > 0.20$, such as a medium to light colored roof, and increases the solar reflectance of a surface with $\rho_{\mathrm{i}} < 0.20$, such as a black roof.

Variation with climate of aged solar reflectance in the CRRC2 site-resolved database

Figure 3 compares measured site-specific aged solar reflectance $\rho_{\mathrm{a},k}$ to measured initial solar reflectance ρ_{i} at each site (FL, AZ, OH) for all products in the CRRC2 site-resolved database. Each graph in the figure includes a black line marking no change ($\rho_{\mathrm{a}} = \rho_{\mathrm{i}}$), a red line representing 2008 Title 24 provisional aged solar reflectance $\rho'_{\mathrm{a,T24}}$, and a green curve showing the running mean. Error bars indicate the dispersion (standard deviation) about $\rho_{\mathrm{a},k}$ of the three aged solar reflectances measured at each site. In most cases, the dispersion was less than 5% of the mean.

These measurements show significant loss of solar reflectance, especially for products with high initial reflectance. This phenomenon is particularly evident for samples weathered in hot-and-humid Florida (Figure 3a), and is least marked for samples in hot-and-dry Arizona (Figure 3b).

Table 3 disaggregates by ρ_{i} quintile the total number of samples, the number and fraction of samples by product type, and the site-specific mean absolute loss in solar reflectance, $\rho_{\mathrm{i}} - \rho_{\mathrm{a},k}$. While the bulk of the data corresponds to the three central quintiles (i.e., to initial solar reflectance in the range $0.2 \le \rho_{\mathrm{i}} < 0.8$), the distribution of initial solar reflectances is not homogeneous across product categories. For example, field-applied coatings (typically light) were mostly in the top two quintiles, while shingles (typically dark) are predominantly in the second quintile. Except for the least reflective materials ($\rho_{\mathrm{i}} < 0.2$), in all cases we observed that products with higher ρ_{i} showed larger loss in ρ. Absolute solar reflectance losses for samples with $\rho_{\mathrm{i}} \ge 0.4$ were 2 - 3 times greater in Florida than in Arizona; losses in Ohio were intermediate.

We note that the reflectance change trends shown in Figure 3 and averaged in Table 3 give more importantance to field-applied coatings (29% of CRRC2) and factory-applied coatings (21% of CRRC2) than to other product types.

Disaggregation by product type

Figure 4 plots $\rho_{\mathrm{a},k}$ vs. ρ_{i} by product type in the CRRC2 site-resolved database. As in Figure 3, the black line marks no change ($\rho_{\mathrm{a}} = \rho_{\mathrm{i}}$), the red line represents 2008 Title 24 provisional aged solar reflectance $\rho'_{\mathrm{a,T24}}$, and the green curve shows the running mean. The solar reflectances of metal and factory-applied coating products were very stable, while those of field-applied coating, single-ply membrane and modified bitumen products declined sharply. Certain product types such as tile and shingle included very few samples with $\rho_{\mathrm{i}} > 0.5$, the range in which aging would be expected to have greatest effect.

The mean fractional difference between aged solar reflectance at site k (FL, AZ, OH) and aged solar reflectance averaged over all three sites,

$$\delta = \frac{(\rho_{\mathrm{a},k} - \rho_{\mathrm{a}})}{\rho_{\mathrm{a}}} \tag{3}$$

is charted for each product type in Figure 5. Error bars mark one standard deviation, and the circled values along the horizontal axis indicate the number of samples in each product type. For most product categories, δ was negative for samples weathered in Florida, positive for samples weathered in Arizona and closer to zero for samples from Ohio, consistent with values reported in Table 4. Smaller fluctuations among sites were observed for product types that exhibit stable solar reflectance, such as factory-applied coating and metal, or that tend to be dark, such as tile and shingle.

Climate-specific values of aged solar reflectance are of particular interest when assessing product performance in a particular part of the U.S. (e.g., hot-and-humid Florida). However, we note that even for product types with significant reflectance losses, δ was always confined to ± 15%. Hence, the three-site average value reported by the CRRC well represents a variety of US climates and pollution levels.

Solar reflectance trends in the CRRC and EPA databases

Both the CRRC and EPA programs require that manufacturers provide measurements of aged solar reflectance and thermal emittance after three years of natural exposure. As noted earlier, the CRRC specifies coupon exposure at three fixed sites (weathering farms in FL, AZ, and OH), while the EPA aged solar reflectance is provided by the manufacturer, and can be an average of in-situ measurements made on three buildings, aged measurements from one climate zone, or taken from CRRC ratings. The EPA program does not standardize its exposure sites, and requires only that at least one building be located in a U.S. major metropolitan area [8]. Another difference is that all products in the EPA database have an initial solar reflectance of at least 0.25. This is because the EPA's ENERGY STAR program requires $\rho_\mathrm{i} \geq 0.25$ and $\rho_\mathrm{a} \geq 0.15$ for steep roofs, and $\rho_\mathrm{i} \geq 0.65$ and $\rho_\mathrm{a} \geq 0.50$ for low-sloped roofs [7]. The CRRC database includes products with $\rho_\mathrm{i} < 0.25$ because they do not set minimum requirements for including products in their database.

Regression analysis

A linear regression of aged solar reflectance ρ_a to initial solar reflectance ρ_i

$$\rho_\mathrm{a} = a + b\ \rho_\mathrm{i} \tag{4}$$

that yields parameters a and b can be rearranged in the form of Eq. (1)

$$\rho_\mathrm{a} = \alpha + \beta\ (\rho_\mathrm{i} - \alpha) \tag{5}$$

by setting $\alpha = a/(1-b)$ and $\beta = b$. These unconstrained, or "free," values of parameters α and β represent the linear fit that minimizes the root mean square (rms) error χ in prediction of aged solar reflectance.

Free parameters α_free and β_free were fit to each product type in each database. To first order, α should be independent of product type because it represents the solar reflectance of an opaque soil layer, rather than resistance to soiling (β). In the 2008 Title 24 formula [Eq. (2)], α is assumed to be 0.20. We repeated each product type regression with α set to 0.10, 0.15, 0.20, 0.25, or 0.30, and compared the rms error of this constrained fit, χ, to that of the unconstrained fit, χ_{free}. We then chose a common value of α, denoted α_0, that yielded $\chi \approx \chi_{\mathrm{free}}$ and was consistent with the range of α_{free} observed for various product types. This offers an expression for predicted aged solar reflectance of the form

$$\rho'_{\mathrm{a}} = \alpha_0 + \beta\left(\rho_{\mathrm{i}} - \alpha_0\right) \tag{6}$$

where α_0 is the same for all product types, and β is fit to each product type.

Overprediction rate analysis

Eq. (6) yields the best linear fit of aged to initial solar reflectance, subject to the constraint that $\alpha = \alpha_0$. However, since measured values of aged solar reflectance tend to be scattered about this line, provisional aged solar reflectances predicted from Eq. (6) will underpredict the measured solar reflectance of some products, and overpredict those of others.

We define the overprediction rate F of a formula for provisional aged solar reflectance as the fraction of products for which predicted aged solar reflectance ρ'_{a} exceeds measured aged solar reflectance ρ_{a}. For example, if $\rho'_{\mathrm{a}} > \rho_{\mathrm{a}}$ for 25% of a given set of products, such as single-ply membranes, the overprediction rate of that formula for that product set is 25%.

Comparison by product type and database

Figure 6 shows for each product type and edited database (CRRC1 and EPA1) the variation of aged solar reflectance with initial solar reflectance. The green line and corresponding equation show the best unconstrained linear fit and its root mean square error χ; the red line represents 2008 Title 24 provisional aged solar reflectance $\rho'_{\mathrm{a,T24}}$; and the black line marks no change ($\rho_{\mathrm{a}} = \rho_{\mathrm{i}}$).

Table 4 summarizes the linear regression analysis for each product type. The soil layer solar reflectance of $\alpha = 0.20$ used in the 2008 T24 formula was found to work well, yielding $\chi_{\alpha=0.20}/\chi_{\mathrm{free}}$ less than 1.07 for all product types in CRRC1, and less than 1.04 for the majority of product types in both CRRC1 and EPA1. Setting α to 0.25 or greater made it difficult to accurately predict the aged solar reflectance of materials with $\rho_{\mathrm{i}} < \alpha$. Hence, we set the common solar reflectance of a soil layer α_0 to 0.20, and show in the first column $\beta_{\alpha=0.20}$, the best-fit value of β for each product type subject to the constraint $\alpha = \alpha_0 = 0.20$.

Overprediction rate F_{T24} for the 2008 Title 24 provisional aged solar reflectance $\rho'_{\mathrm{a,T24}}$ computed using Eq. (2) is shown by product type and database in Table 5.

We make the following observations.

Factory-applied coating and metal (CRRC1). These two product types exhibit strong and essentially identical retention of solar reflectance ($\beta_{\alpha=0.20}$=0.95 and 0.94, respectively). The provisional aged solar reflectance predicted by 2008 Title 24 rarely exceeds measured aged solar reflectance, with overprediction rates $F_{\mathrm{T24}} \leq 5\%$. Regressions were tight with $\chi_{\mathrm{free}} = 0.013$ and 0.011 for factory-applied coating and metal, respectively. We note that factory-applied coating and metal products were expected to perform very similarly because as of April 2011 most CRRC-rated factory-applied coating products in the CRRC1 database are intended for metal substrates.

In an earlier study of soiling of coated metal products in California [16], more dust was found near the end of the dusty summer period than is evident from the aged solar reflectances shown in Figure 4a. This suggests that aged solar reflectance may be affected by the length of time since the last rain and that handling may inadvertently dislodge loose dust.

Field-applied coating (CRRC1, EPA1). All field-applied coating products in the CRRC1 and EPA1 databases with $\rho_{\mathrm{i}} > 0.6$ lose solar reflectance ($\beta_{\alpha=0.20}$=0.76 - 0.77). $\rho'_{\mathrm{a,T24}}$ frequently overpredicts aged solar reflectance, with F_{T24} of 30% for CRRC and 20% for EPA. Both databases show similar trends and a great deal of scatter about the unconstrained fit ($\chi_{\mathrm{free}} \approx 0.07$).

Modified bitumen (CRRC1). The CRRC1 database includes modified bitumen products with a wide range of ρ_{i} (about 0.25 - 0.88), showing a soiling resistance ($\beta_{\alpha=0.20}$=0.79) nearly identical to those seen for field-applied coating products in the CRRC1 and EPA1 databases, and a Title 24 overprediction rate F_{T24} of 16%. There is a moderate amount of scatter ($\chi_{\mathrm{free}} \approx 0.04$) for this product category.

The modified bitumen products are grouped in three categories of initial solar reflectance: high initial solar reflectance (i.e., white), medium initial solar reflectance, and "low" initial solar reflectance (near 0.3). The low reflectance products likely correspond to asphaltic surfaces with a pressed layer of roofing granules. That is, they have structure very similar to that of an asphalt shingle. We note that the asphalt shingle data essentially also falls on a no-change line passing through the point (0.3, 0.3). The tentative conclusion is that the initial and aged values of reflectance for granulated surfaces are approximately equal (within about ± 0.03). However, further analysis of CRRC2 shows that in Florida, the low reflectance products fall below the no-change line. Presumably this behavior is a consequence of the humid climate and the low-slope (5% tilt) exposure.

Modified bitumen (EPA1). The EPA1 database includes modified bitumen products with a limited range of ρ_{i} (about 0.65 - 0.90). The combination of small population (n=19), limited initial solar reflectance range and high scattter ($\chi_{\mathrm{free}} \approx 0.08$) restrict our analysis, and the regression equation should be not be used.

Shingle (CRRC1, EPA1). The CRRC1 and EPA1 databases each contain ~ 20 shingle products, with no values of $\rho_{\mathrm{i}} > 0.30$ in the former and only two values of $\rho_{\mathrm{i}} > 0.35$ in the latter. The data set is too limited in scope to draw conclusions at this time, and the regression equation should not be used. However, we do observe that many of the low ρ_{i} products in the CRRC database tended to gain solar reflectance. This could happen if the soil layer is more reflective than the product, or from the evaporation of oils [5, 17].

Single-ply membrane (CRRC1, EPA1). Nearly all single-ply membrane products in the CRRC1 and EPA1 databases lose solar reflectance, but exhibit soiling resistance ($\beta_{\alpha=0.20}$ =0.79-0.82) slightly greater than those of field-applied coating products in the CRRC1 and EPA1 databases (0.76-0.77) and similar to that of modified bitumen products in the CRRC1 database

(0.79). The Title 24 overprediction rate F_{T24} is about 18% for CRRC1 and 24% for EPA1. Scatter is moderate for CRRC1 ($\chi_{\mathrm{free}} \approx 0.05$) and large for EPA1 ($\chi_{\mathrm{free}} \approx 0.08$).

Tile (CRRC1). The solar reflectance of tile products in the CRRC1 database was stable when $\rho_{\mathrm{i}} < 0.40$, but otherwise generally decreased with aging. Soiling resistance was high ($\beta_{\alpha=0.20}$=0.88), and the Title 24 overprediction rate was low (F_{T24}=6%). The range of ρ_{i} was fairly wide (about 0.30 - 0.80) and scatter was low ($\chi_{\mathrm{free}} \approx 0.02$).

Tile (EPA1). Tile products in the EPA1 database were unusual in that while most products lost reflectance, a fair number with initial solar reflectance in the range of 0.25 - 0.50 actually *gained* solar reflectance. Soiling resistance ($\beta_{\alpha=0.20}$=0.82) was comparable to that of single-ply membrane. The Title 24 overprediction rate (F_{T24}=30%) was comparable to that for field-applied coatings in CRRC1 (30%). We caution that these results and the regression equation may be distorted by the gains in solar reflectance, which in turn might result from measurement error (e.g., measuring initial and aged solar reflectances on different regions of a multicolor tile assembly).

Quantification of solar reflectance loss

All else being equal, lighter surfaces tend to lose more reflectance than darker surfaces. Hence, another metric that can be used to compare the values reported in the culled public CRRC1 and EPA1 databases is fractional loss of solar reflectance,

$$\phi = \frac{\rho_{\mathrm{i}} - \rho_{\mathrm{a}}}{\rho_{\mathrm{i}}} . \tag{7}$$

It can be applied to the average of results corresponding to each product category, or to the total data of each database grouped by quintiles. Figure 7 shows mean values of ϕ disaggregated by product type and database, with error bars marking one standard deviation.

The three product types most affected by soiling include field-applied coating, modified bitumen and single-ply membrane, with ϕ between 5% and 20%. For these products, results from each database were coincident within the variability of the data (illustrated in Figure 7 with error bars corresponding to ± one standard deviation). Darker materials such as shingle and tile exhibit lower fractional loss of solar reflectance, or in the case of shingles can even increase their solar reflectance upon aging.

Product-specific estimation of provisional aged solar reflectance

Figure 8 graphs for each product type the overprediction rate F versus β when provisional aged solar reflectance is computed from Eq. (6) subject to $\alpha_0 = 0.20$, such that

$$\rho'_{\mathrm{a}} = 0.20 + \beta\,(\rho_{\mathrm{i}} - 0.20). \tag{8}$$

Table 6 shows by database (CRRC1 and EPA1) and product type the largest value of soiling resistance β that will yield a specific overprediction rate F (5%, 10%, 15%, 20%, 30% ..., 90%). It can be used to create product-specific formulas for provisional aged solar reflectance by choosing a target overprediction rate, such as 10%, then reading off the value β to substitute into Eq. (8). For example, setting $\beta = 0.59$ will limit the overprediction rates for CRRC field-applied coating products to 10%. However, we stress the following caveats.

1. Only CRRC database results should be used, since Title 24 references CRRC product ratings for roofing products.

2. At this time there are too few aged shingle products in the CRRC database to design a product-specific formula.

3. The target overprediction rate is a policy, rather than technical, choice. For example, one might set F =10% to create a conservative formula that rarely overpredicts aged solar reflectance, or F =50% to yield a formula that is just as likely to overpredict ρ_{a} as underpredict ρ_{a}.

Conclusions

After editing the public CRRC and EPA databases to exclude values that were duplicative or unmeasured, and creating a CRRC database with site-specific measurements by transcribing paper records, we draw the following conclusions.

1. Many products suffer significant loss of solar reflectance, especially for those with high initial solar reflectance. Products with very low initial solar reflectance ($\rho_{\mathrm{i}} < 0.2$) tend to become more reflective as they age. Within the CRRC2 site-resolved database, absolute solar reflectance losses for samples with $\rho_{\mathrm{i}} \geq 0.4$ were 2 - 3 times greater in Florida than in Arizona; losses in Ohio were intermediate.

2. It is reasonable for all product types to relate measured aged solar reflectance ρ_{a} to measured initial solar reflectance ρ_{i} with an expression of the form $\rho_{\mathrm{a}} = \alpha_0 + \beta\left(\rho_{\mathrm{i}} - \alpha_0\right)$, where α_0 represents the solar reflectance of an opaque soil layer, and β represents the soiling resistance of the product type. The root mean square error of this fit is small for factory-applied coating and metal products, but substantial for field-applied coating and single-ply membrane products.

3. With $\alpha_0 = 0.20$, best-fit values of β for product types in the CRRC1 edited database range from 0.76 for field-applied coating to 1.09 for shingle. The EPA1 edited database gave similar results. The soiling resistance $\beta > 1$ for CRRC shingle products may result from processes other than soiling, such as the evaporation of oils from shingle granules.

4. The 2008 Title 24 provisional aged solar reflectance formula overpredicts the measured aged solar reflectance of 0% to 30% of each product type in the CRRC1 edited database. The rate of overprediction was greatest for field-applied coating, modified bitumen, and single-ply membrane products and least for factory-applied coating, metal, and tile products. Shingle products also have a low rate of overprediction but there are not enough data points to generalize this conclusion.

5. Product-specific formulas of the form $\rho'_{\mathrm{a}} = 0.20 + \beta\left(\rho_{\mathrm{i}} - 0.20\right)$ can be used to estimate provisional aged solar reflectance pending measurement of aged solar reflectance. The appropriate value of β varies by product type and should be selected to attain some desired overprediction rate for the formula. For example, to attain an overprediction rate of 10% one would choose $\beta = 0.59$ for field-applied coating products and $\beta = 0.82$ for factory-applied coating products. *The target overprediction rate is a policy, rather than technical, choice.*

6. There is generally too much scatter about each product type's regression line to accurately predict aged solar reflectance from initial solar reflectance for individual products. We recommend using the correlations developed in this study only to generate for each product type a formula for provisional aged solar reflectance. The latter represents a lower bound to aged solar reflectance (at some selected overprediction rate).

7. The correlations for shingle products presented in this paper should not be used to predict aged solar reflectance or estimate a provisional aged solar reflectance because the data set is too small and too limited in range of initial solar reflectance. More measurements are needed.

Finally, we note that our analysis may be refined as the CRRC and EPA databases grow.

Acknowledgements

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Appendix: Relating opaque and translucent soiling models

In some earlier work [5, 16] a simple optical model of soiling effects on solar reflectance has been employed in which the soil layer is assumed to be translucent and to fully cover the surface. Let r_{soil} and a_{soil} be the solar reflectance and solar absorptance of the soil layer, each parameter small compared to 1. Then it has been found that

$$\rho_{\text{a}} = \rho_{\text{i}} - 2\, a_{\text{soil}}\, \rho_{\text{i}} + (1-\rho_{\text{i}})^2\, r_{\text{soil}} \tag{A-1}$$

which expresses the aged solar reflectance ρ_{a} as a function of the soiling parameters r_{soil} and a_{soil} and the initial reflectance ρ_{i}. This expression is analogous to Eq. (1). However, Eq. (1) introduces differing parameters α and β, is linear rather than quadratic in ρ_{i}, and assumes that the soil layer is opaque. Since plots of ρ_{a} vs. ρ_{i} based on Eq. (A-1) are almost linear in ρ_{i}, we can relate the two approaches by equating values of ρ_{a} for the extreme values at $\rho_{\text{i}} = 0$ and $\rho_{\text{i}} = 1$. We find that $r_{\text{soil}} \approx \alpha(1-\beta)$ and $a_{\text{soil}} \approx \frac{1}{2}(1-\alpha)(1-\beta)$.

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Tables

Table 1. CRRC and EPA product type values referenced by our product type definitions.

Product type	CRRC values	EPA values
Factory-applied coating	Factory-applied coating	*
Field-applied coating	Field-applied coating	*
Metal	Metal	Metal
Modified bitumen	Modified bitumen	Modified bitumen
Shingle	Shingle or shake	Shingle
Single-ply membrane	Single-ply thermoplastic Single-ply thermoset	Single-ply
Tile	Tile or slate**	Tile

* The EPA database does not specify whether coatings are factory-applied or field-applied. A sampling of field-applied coatings in the EPA database was identified by randomly selecting products marked “coating,” then determining from manufacturer websites whether each product is field applied.

** Excluding polymer products categorized as “tile or slate”.

Table 2. Derivations of CRRC and EPA roofing product databases.

Name	Description	Notes	Number of products*
CRRC0	CRRC Rated Products Directory (online April 2011)	CRRC provided an augmented version of their online directory. The augmented version included the same products as the online version but included additional details permitting identification of duplicative and/or non-measured values.	1357
CRRC1	Edited version of CRRC0	We removed duplicative values stemming from licensed resellers and Color Family additional elements from CRRC0. Values for Color Family representative elements are measured rather than "default" values.	662
CRRC2	Site-resolved database transcribed from CRRC's paper records in December 2010	We transcribed values for each of the nine coupons per product used to determine initial and aged CRRC product ratings. We omitted products from licensed resellers and Color Family additional elements (i.e., those containing duplicative values). For Color Family representative elements we recorded measured values and not default values. CRRC2 contains fewer products than CRRC1 mostly because some paper records were missing or overlooked.	586
EPA0	EPA ENERGY STAR® Roof Product List (online March 2011)	Downloaded from http://www.energystar.gov	5397
EPA1	Edited version of EPA0	We removed metal and factory-applied coating products since we were unable to identify which were members of a Color Family. We randomly selected 243 of the 1987 coating products with aged ratings and from these identified 98 that were field-applied coatings based on product data. These 98 field-applied coatings were restored in EPA1.	263

*Number of products with 3-year aged ratings.

Table 3. Number of samples and mean absolute loss in measured solar reflectance within each quintile of initial solar reflectance, shown for the CRRC2 site-resolved database.

	Initial solar reflectance, ρ_i				
	0.0 – 0.2	**0.2 – 0.4**	**0.4 – 0.6**	**0.6 – 0.8**	**0.8 – 1.0**
Number of samples by quintile and product type [(a)]					
All	5 (100%)	198 (100%)	151 (100%)	225 (100%)	7 (100%)
Factory-applied coating	0 (0%)	76 (38%)	26 (17%)	22 (10%)	0 (0%)
Field-applied coating	0 (0%)	6 (3%)	44 (29%)	119 (53%)	4 (57%)
Metal	4 (80%)	18 (9%)	6 (4%)	5 (2%)	0 (0%)
Modified bitumen	0 (0%)	39 (20%)	15 (10%)	17 (8%)	0 (0%)
Shingle	0 (0%)	13 (7%)	0 (0%)	0 (0%)	0 (0%)
Single-ply membrane	0 (0%)	0 (0%)	9 (6%)	24 (11%)	1 (14%)
Tile	0 (0%)	12 (6%)	14 (9%)	1 (0.4%)	0 (0%)
Other	1 (20%)	34 (17%)	37 (25%)	37 (16%)	2 (29%)
Mean absolute loss in solar reflectance, $\rho_\mathrm{i} - \rho_\mathrm{a}$ [(b)]					
Florida	-0.007 ± 0.020	0.012 ± 0.017	0.050 ± 0.069	0.133 ± 0.126	0.238 ± 0.146
Arizona	-0.010 ± 0.024	0.002 ± 0.014	0.012 ± 0.031	0.046 ± 0.058	0.077 ± 0.060
Ohio	0.002 ± 0.023	0.009 ± 0.015	0.037 ± 0.040	0.101 ± 0.075	0.173 ± 0.092

(a) Fractions describe product type distribution within each quintile.

(b) Error estimates represent one standard deviation.

Table 4**.** Results of linear regressions of the form $\rho_{\mathrm{a}} = \alpha + \beta(\rho_{\mathrm{i}} - \alpha)$, showing fitted soiling resistance $\beta_{\alpha=0.20}$ when soil layer reflectance α is set to 0.20; α_{free} , β_{free} and root mean square error χ_{free} obtained from a free (unconstrained) fit; and the ratio of χ to χ_{free} when the fit is constrained by setting α to 0.10, 0.15, 0.20, 0.25 or 0.30.

					$\chi/\chi_{\mathrm{free}}$				
	$\beta_{\alpha=0.20}$	α_{free}	β_{free}	χ_{free}	$\alpha = 0.10$	$\alpha = 0.15$	$\alpha = 0.20$	$\alpha = 0.25$	$\alpha = 0.30$
<u>CRRC1 (edited CRRC database)</u>									
Factory-applied coating (n=173)	0.95	0.08	0.97	0.013	1.000	1.005	1.018	1.047	1.103
Field-applied coating (n=248)	0.76	0.34	0.69	0.077	1.011	1.008	1.005	1.002	1.001
Metal (n=44)	0.94	0.19	0.94	0.011	1.029	1.007	1.001	1.038	1.152
Modified bitumen (n=71)	0.79	0.23	0.77	0.035	1.094	1.043	1.006	1.008	1.081
Shingle (n=21)	1.09	0.28	0.58	0.012	1.051	1.055	1.064	1.121	1.011
Single-ply membrane (n=34)	0.79	0.35	0.72	0.047	1.072	1.054	1.035	1.018	1.005
Tile (n=52)	0.88	0.28	0.83	0.022	1.103	1.073	1.039	1.009	1.004
<u>EPA1 (edited EPA database)</u>									
Factory-applied coating (n=0)	-	-	-	-	-	-	-	-	-
Field-applied coating (n=98)	0.77	0.30	0.73	0.065	1.005	1.003	1.002	1.001	1.000
Metal (n=0)	-	-	-	-	-	-	-	-	-
Modified bitumen (n=19)	0.78	0.66	0.08	0.076	1.155	1.150	1.143	1.135	1.127
Shingle (n=19)	0.97	0.32	0.95	0.028	1.020	1.017	1.013	1.007	1.001
Single-ply membrane (n=73)	0.82	0.46	0.68	0.082	1.012	1.011	1.009	1.007	1.005
Tile (n=54)	0.82	0.23	0.79	0.047	1.027	1.014	1.003	1.002	1.035

Table 5. Overprediction rate F (%) by product type and database (CRRC1 and EPA1) for the 2008 Title 24 provisional aged solar reflectance formula [Eq. (2)].

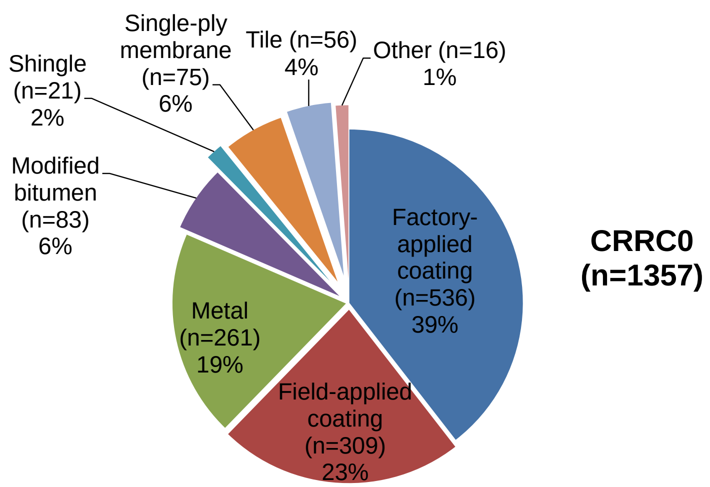
	CRRC1	EPA1
Factory-applied coating	2.9	-
Field-applied coating	30.2	19.6
Metal	4.5	-
Modified bitumen	15.5	42.1
Shingles	0.0	15.8
Single-ply membrane	17.6	24.0
Tile	5.8	29.6

Table 6. Largest value of soiling resistance β yielding a provisional aged solar reflectance formula with the specified overprediction rate F for each product type and database. Formula applies Eq. (6) with a common soil layer solar reflectance of $\alpha_0 = 0.20$. NA indicates that the specified overprediction rate can not be attained in this manner.

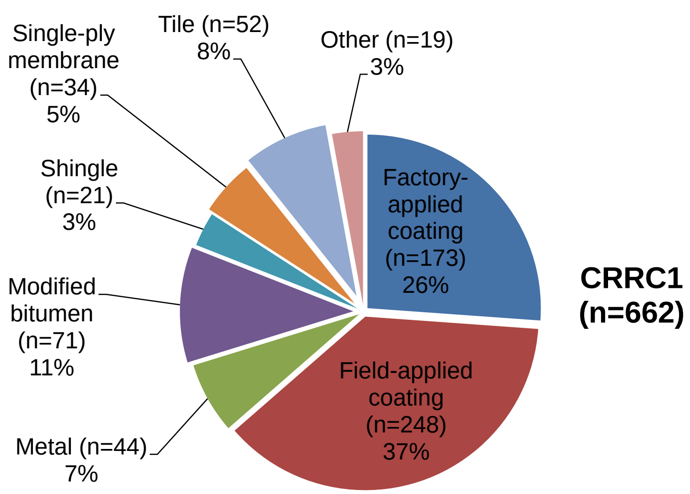
	F = 5%	F = 10%	F = 15%	F =20%	F = 30%	F = 40%	F = 50%	F = 60%	F = 70%	F = 80%	F = 90%
CRRC1 (edited CRRC database)											
Factory-applied coating (n=173)	0.73	0.82	0.85	0.88	0.91	0.94	0.95	0.96	0.98	NA	NA
Field-applied coating (n=248)	0.52	0.59	0.62	0.66	0.69	0.75	0.80	0.82	0.85	0.88	0.93
Metal (n=44)	0.71	0.81	0.83	0.85	0.88	0.90	0.92	0.96	0.97	NA	NA
Modified bitumen (n=71)	0.57	0.61	0.66	0.70	0.73	0.75	0.78	0.82	0.88	0.95	NA
Shingle (n=21)	0.85	0.85	0.85	0.88	NA	NA	NA	NA	NA	NA	NA
Single-ply membrane (n=34)	0.61	0.68	0.68	0.70	0.78	0.80	0.83	0.84	0.85	0.87	0.90
Tile (n=52)	0.68	0.80	0.81	0.83	0.87	0.90	0.91	0.93	0.94	NA	NA
EPA1 (edited EPA database)											
Factory-applied coating (n=0)	-	-	-	-	-	-	-	-	-	-	-
Field-applied coating (n=98)	0.56	0.60	0.67	0.70	0.71	0.75	0.78	0.81	0.84	0.87	0.90
Metal (n=0)	-	-	-	-	-	-	-	-	-	-	-
Modified bitumen (n=19)	0.60	0.61	0.62	0.62	0.63	0.67	0.81	0.88	0.93	0.93	0.97
Shingle (n=19)	0.45	0.55	0.55	0.71	0.89	NA	NA	NA	NA	NA	NA
Single-ply membrane (n=73)	0.56	0.57	0.64	0.68	0.76	0.80	0.83	0.85	0.91	0.96	0.98
Tile (n=54)	NA	NA	0.50	0.54	0.75	0.80	0.87	0.91	NA	NA	NA

Figures

(a)


Single-ply membrane (n=75) 6%
Tile (n=56) 4%
Other (n=16) 1%
Shingle (n=21) 2%
Modified bitumen (n=83) 6%
Factory-applied coating (n=536) 39%
Metal (n=261) 19%
Field-applied coating (n=309) 23%
CRRC0 (n=1357)

(b)


Single-ply membrane (n=34) 5%
Tile (n=52) 8%
Other (n=19) 3%
Shingle (n=21) 3%
Factory-applied coating (n=173) 26%
Modified bitumen (n=71) 11%
Field-applied coating (n=248) 37%
Metal (n=44) 7%
CRRC1 (n=662)

(c)

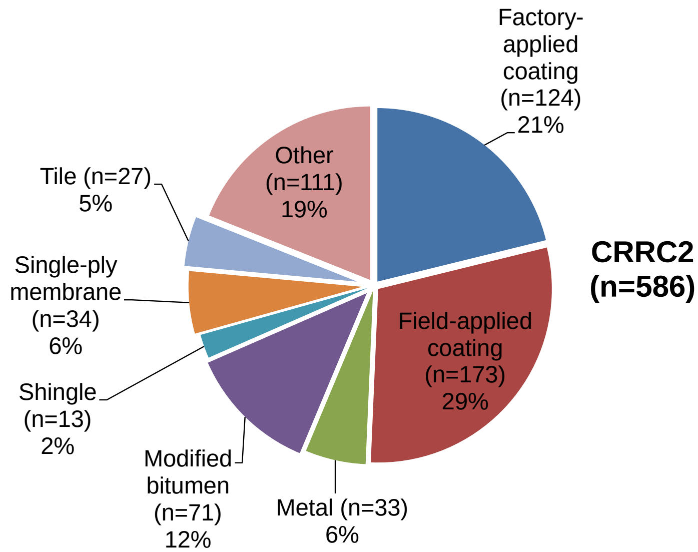
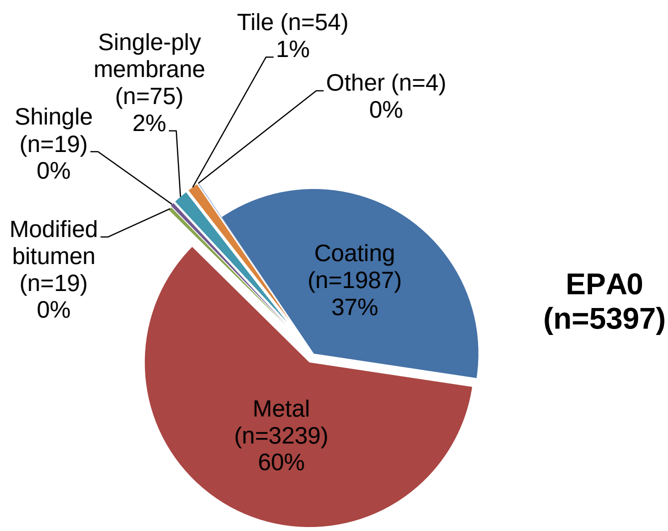


Figure 1. Product distributions in (a) the CRRC0 raw CRRC roofing product database for products with aged ratings, (b) the CRRC1 edited CRRC roofing product database, and (c) the CRRC2 site-resolved CRRC database.

(a)



(b)

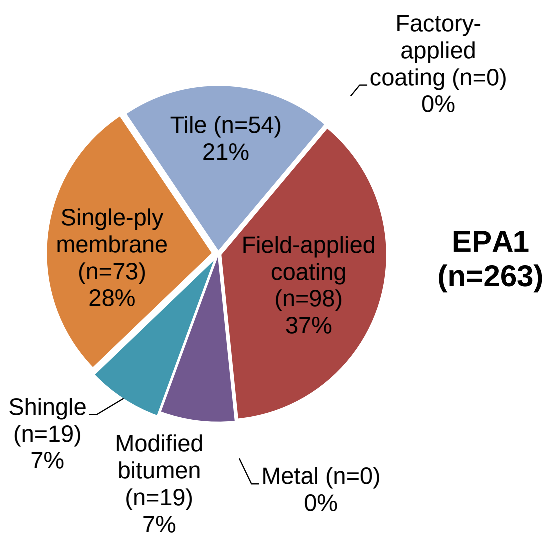
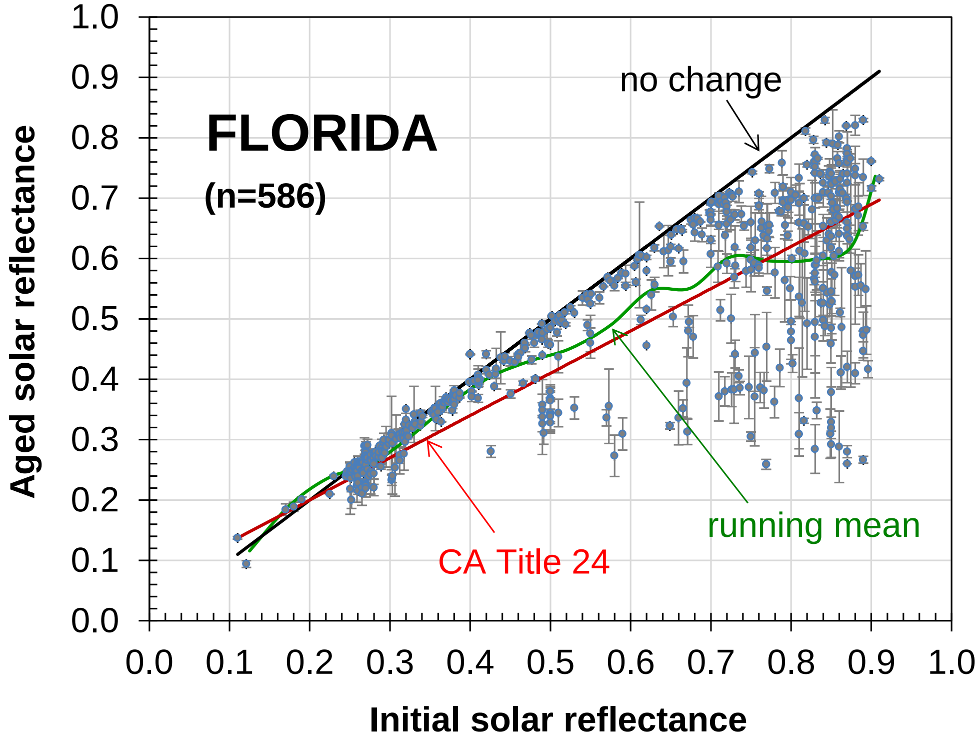
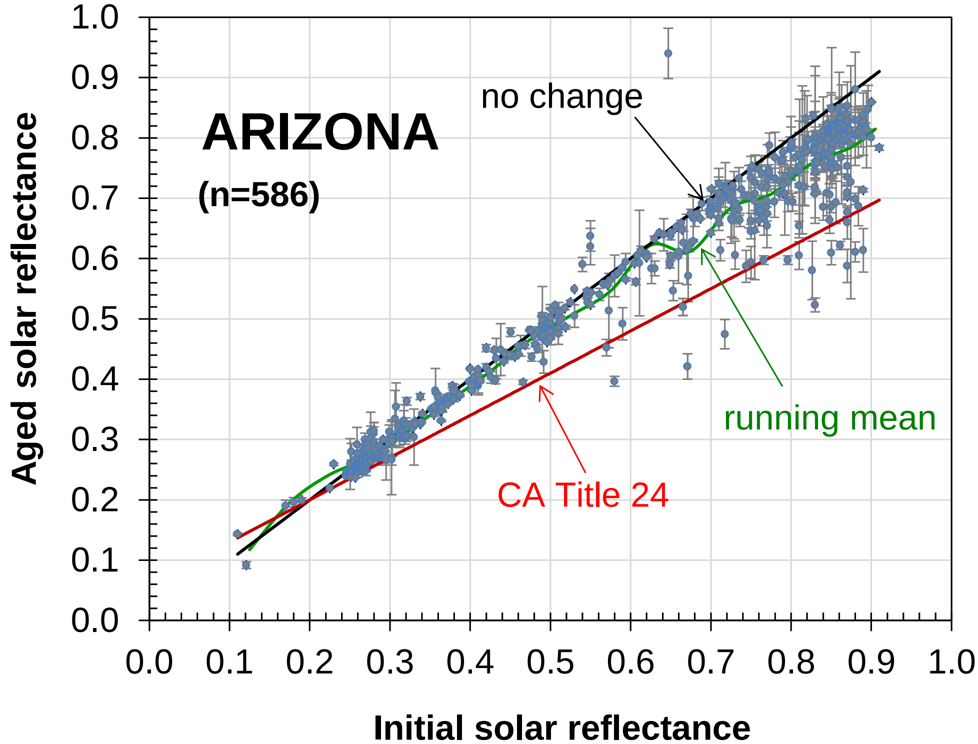


Figure 2. Product distributions in (a) the EPA0 raw EPA roofing product database and (b) the EPA1 edited EPA database analyzed in the current study

(a)


FLORIDA
(n=586)
no change
running mean
CA Title 24
Aged solar reflectance
Initial solar reflectance
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

(b)


ARIZONA
(n=586)
no change
running mean
CA Title 24
Aged solar reflectance
Initial solar reflectance
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

(c)

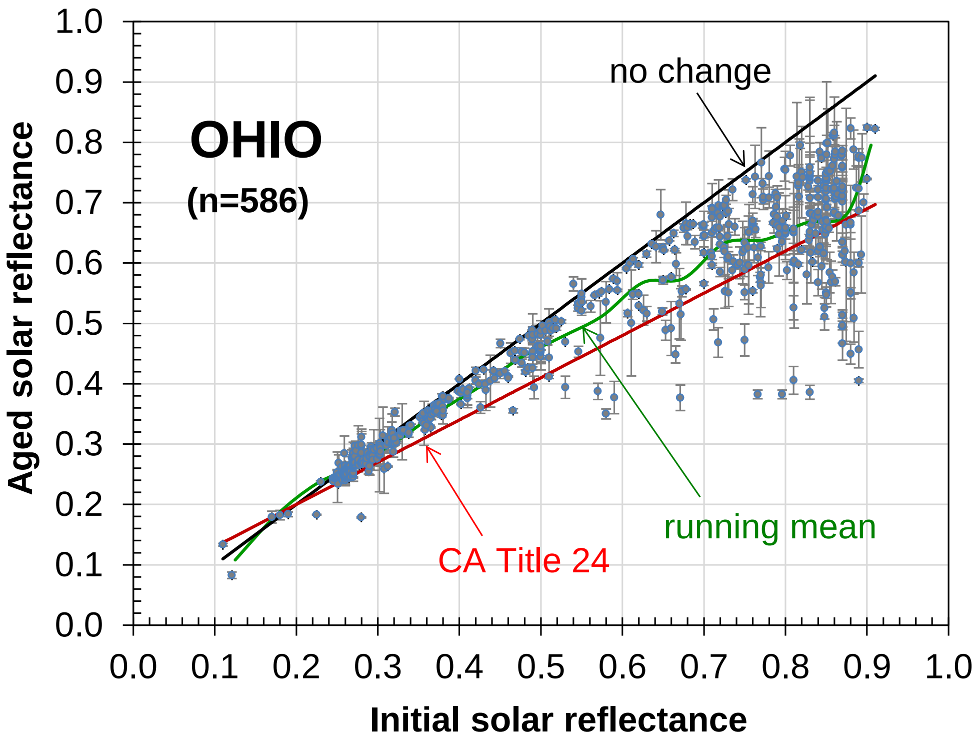
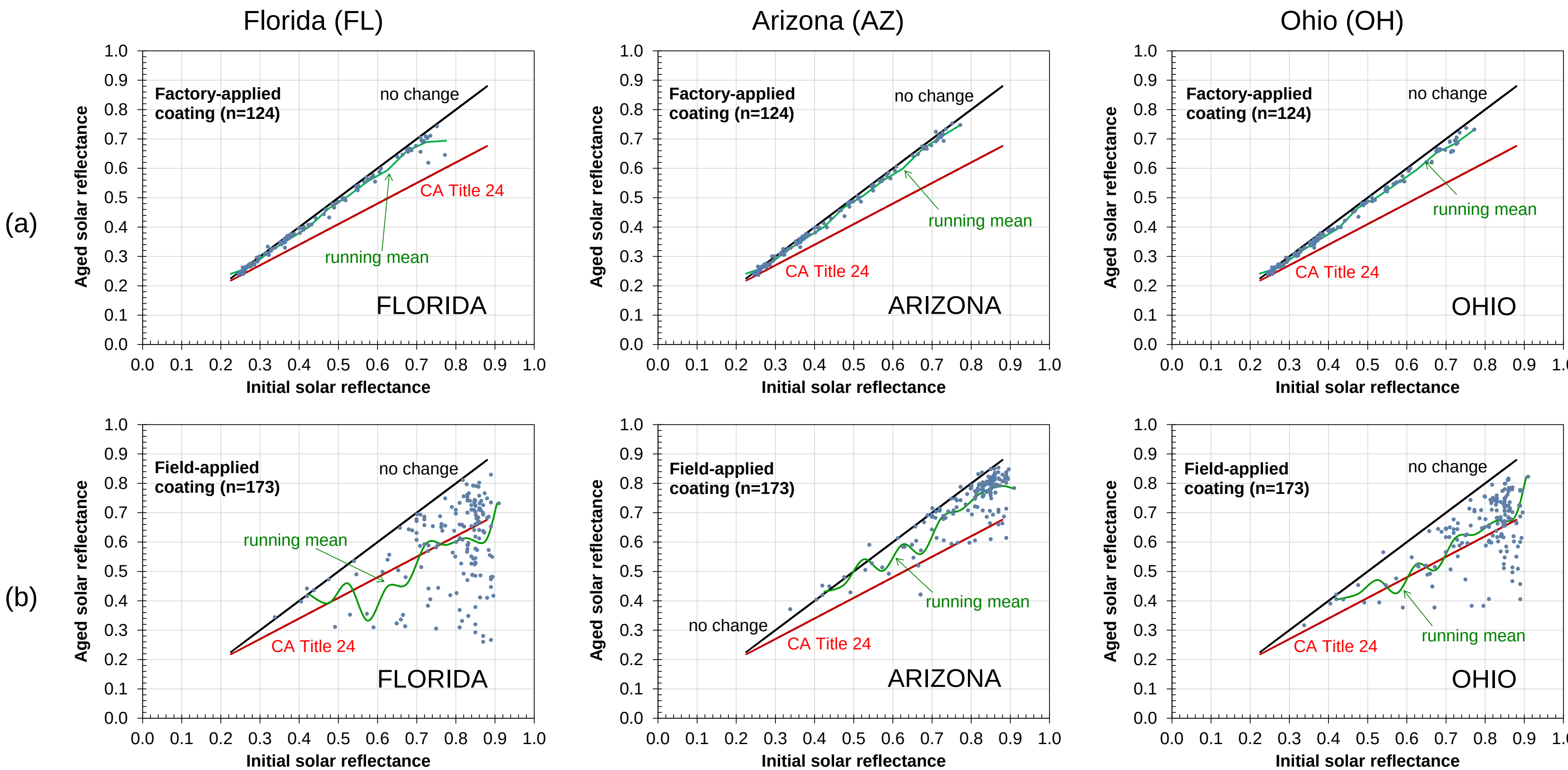
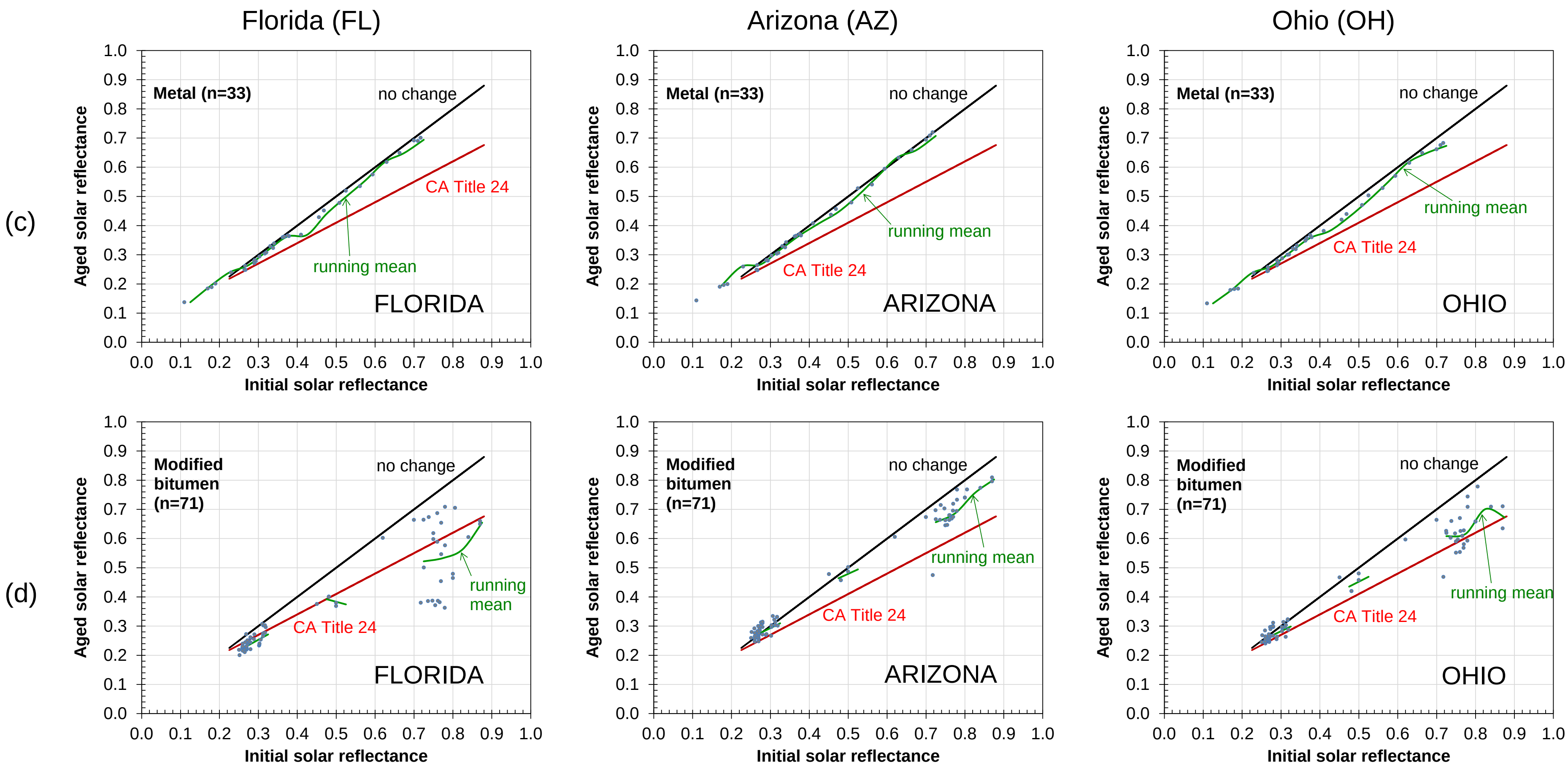
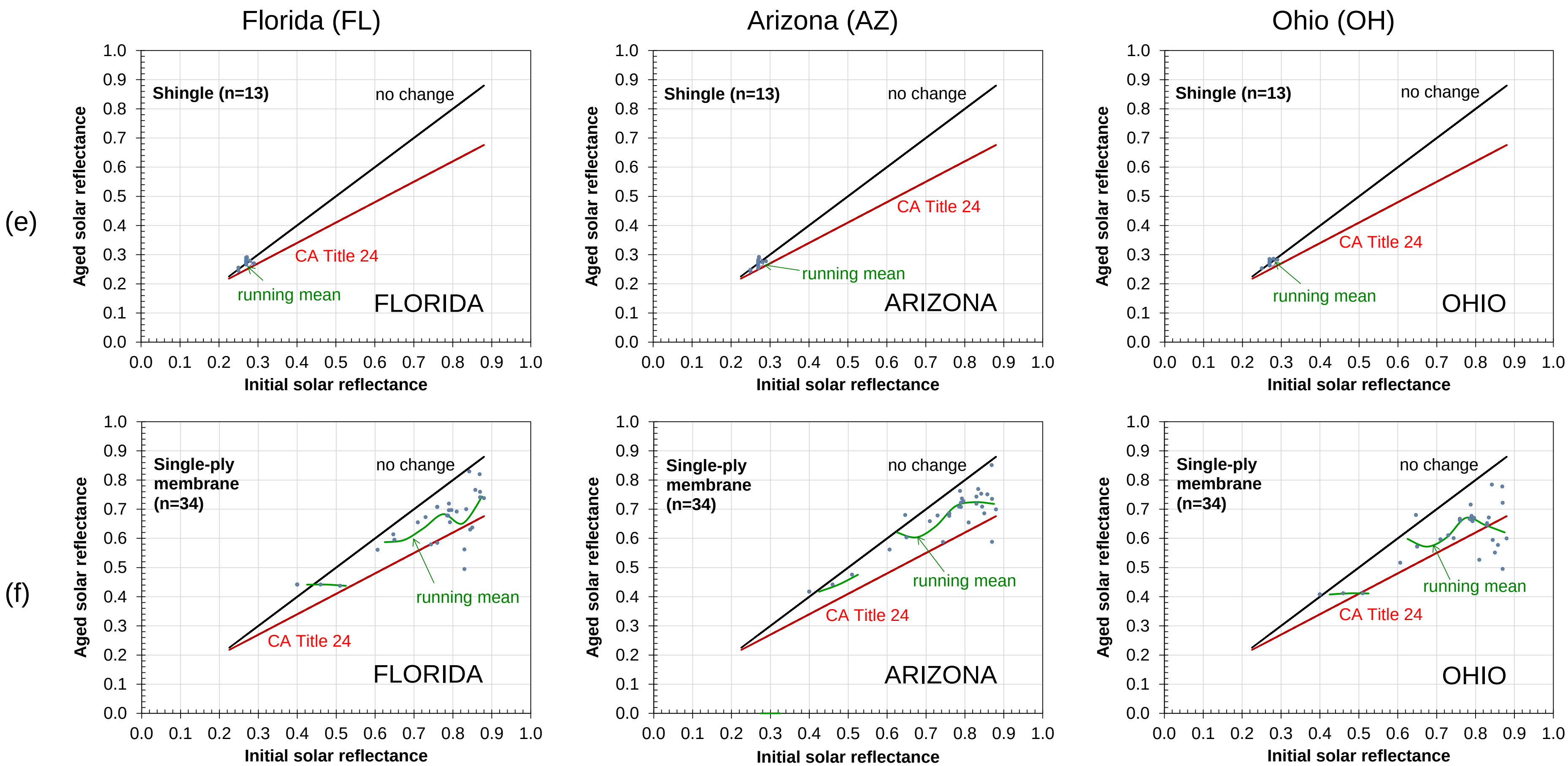


Figure 3. Aged solar reflectance $\rho_{a,k}$ vs. initial solar reflectance ρ_i of all samples in the CRRC2 site-resolved database, shown after three years of exposure in (a) Florida (hot and humid); (b) Arizona (hot and dry); and (c) Ohio (temperate and polluted). Error bars mark one standard deviation in $\rho_{a,k}$.



Florida (FL)
Arizona (AZ)
Ohio (OH)
(a)
(b)
Factory-applied coating (n=124)
Field-applied coating (n=173)
no change
CA Title 24
running mean
FLORIDA
ARIZONA
OHIO
Aged solar reflectance
Initial solar reflectance


Florida (FL)
Arizona (AZ)
Ohio (OH)
(c)
Metal (n=33)
no change
CA Title 24
running mean
FLORIDA
ARIZONA
OHIO
Aged solar reflectance
Initial solar reflectance
(d)
Modified bitumen (n=71)
no change
CA Title 24
running mean
FLORIDA
ARIZONA
OHIO
Aged solar reflectance
Initial solar reflectance


Florida (FL)
Arizona (AZ)
Ohio (OH)
(e)
(f)
Shingle (n=13)
Single-ply membrane (n=34)
no change
CA Title 24
running mean
FLORIDA
ARIZONA
OHIO
Aged solar reflectance
Initial solar reflectance

(g)

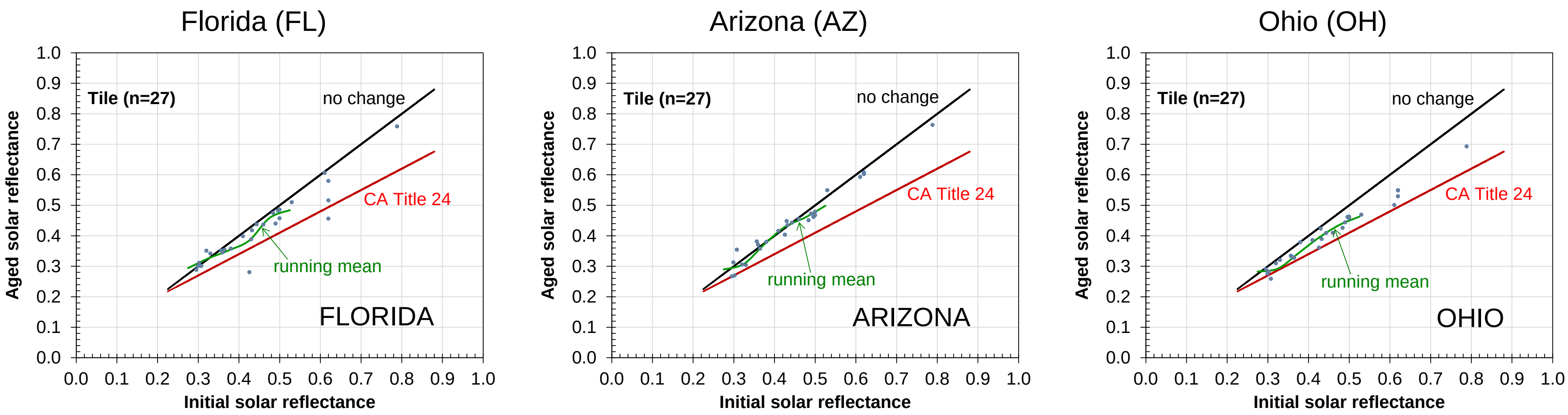


Figure 4. Aged solar reflectance $\rho_{a,k}$ in Florida, Arizona and Ohio vs. initial solar reflectance ρ_i for (a) factory-applied coating, (b) field-applied coating, (c) metal, (d) modified bitumen, (e) shingle, (f) single-ply membrane, and (g) tile roofing products in the CRRC2 site-resolved database.

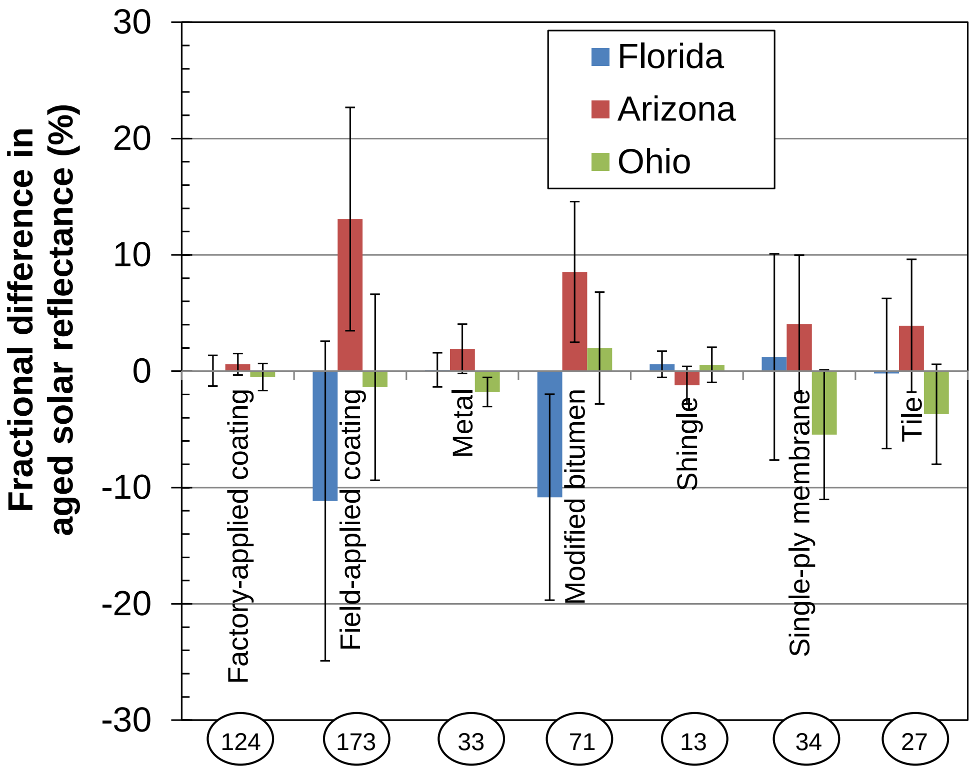
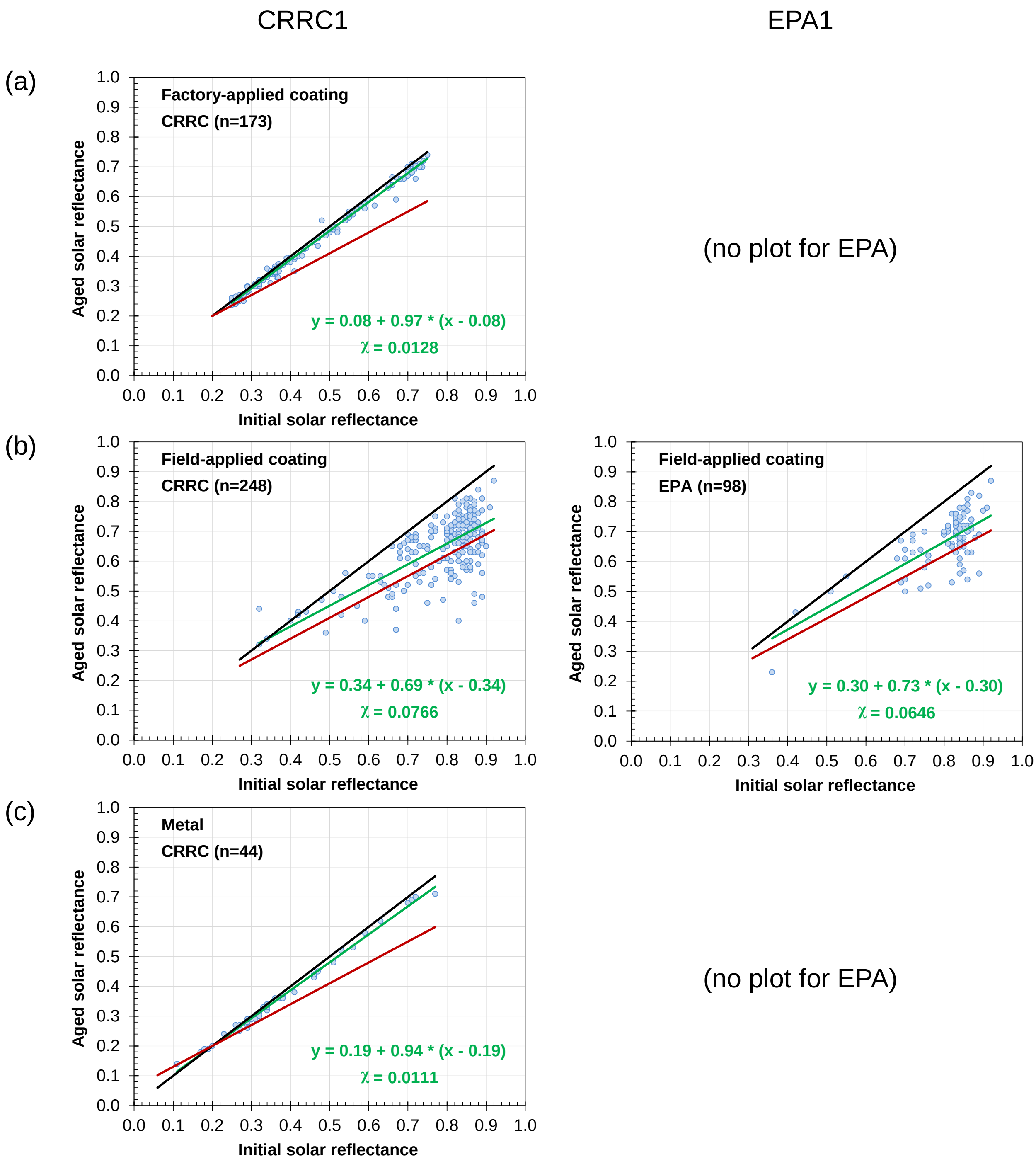
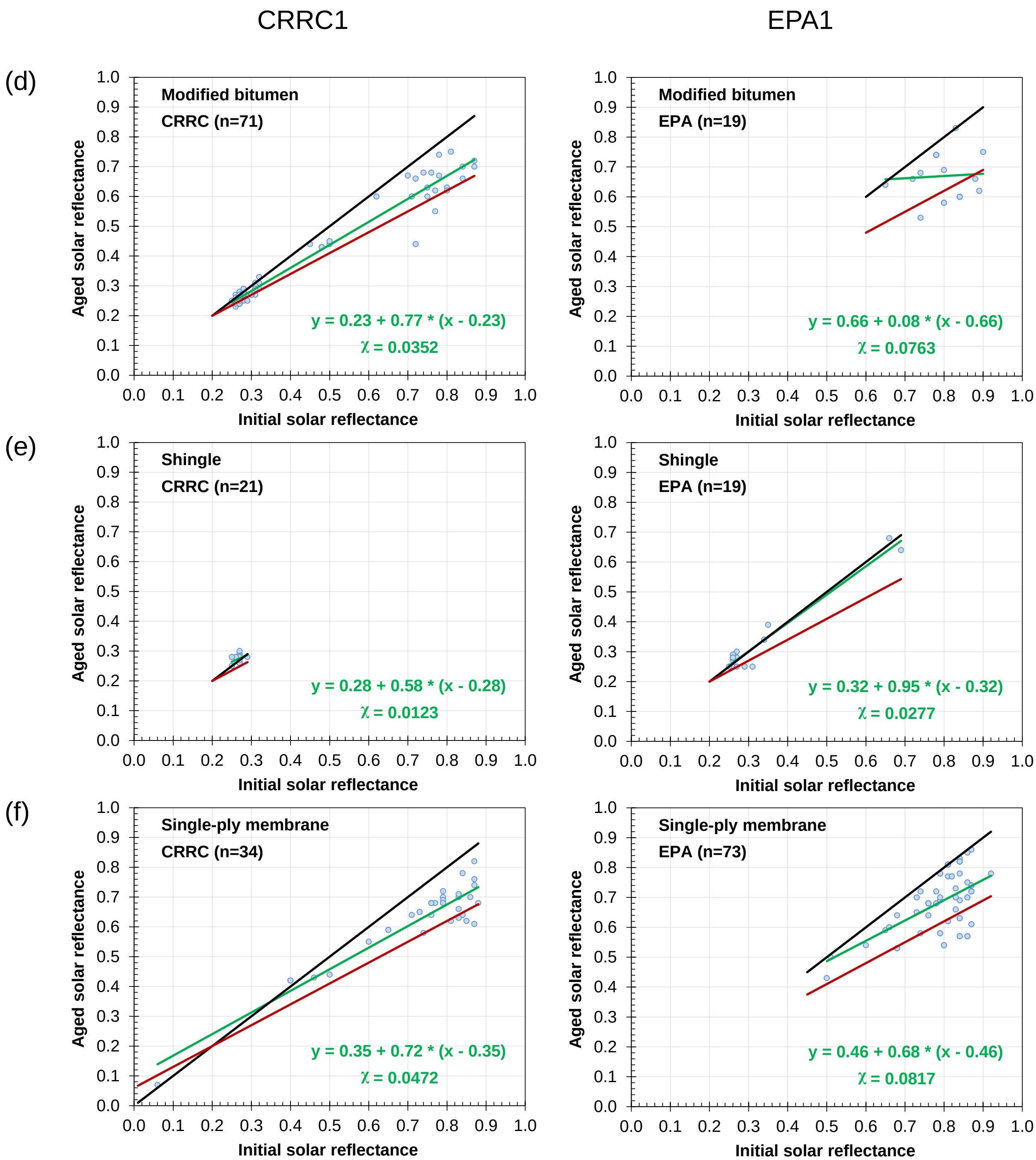


Figure 5. Fractional difference δ between site-specific aged solar reflectance, $\rho_{a,k}$ and three-site average solar reflectance, ρ_a, by product type in the CRRC2 database. Error bars mark one standard deviation; circled values are product counts.



CRRC1
EPA1
(a)
Factory-applied coating
CRRC (n=173)
y = 0.08 + 0.97 * (x - 0.08)
χ = 0.0128
Aged solar reflectance
Initial solar reflectance
(no plot for EPA)
(b)
Field-applied coating
CRRC (n=248)
y = 0.34 + 0.69 * (x - 0.34)
χ = 0.0766
Aged solar reflectance
Initial solar reflectance
Field-applied coating
EPA (n=98)
y = 0.30 + 0.73 * (x - 0.30)
χ = 0.0646
Aged solar reflectance
Initial solar reflectance
(c)
Metal
CRRC (n=44)
y = 0.19 + 0.94 * (x - 0.19)
χ = 0.0111
Aged solar reflectance
Initial solar reflectance
(no plot for EPA)


CRRC1
EPA1
(d)
Modified bitumen
CRRC (n=71)
y = 0.23 + 0.77 * (x - 0.23)
χ = 0.0352
Modified bitumen
EPA (n=19)
y = 0.66 + 0.08 * (x - 0.66)
χ = 0.0763
(e)
Shingle
CRRC (n=21)
y = 0.28 + 0.58 * (x - 0.28)
χ = 0.0123
Shingle
EPA (n=19)
y = 0.32 + 0.95 * (x - 0.32)
χ = 0.0277
(f)
Single-ply membrane
CRRC (n=34)
y = 0.35 + 0.72 * (x - 0.35)
χ = 0.0472
Single-ply membrane
EPA (n=73)
y = 0.46 + 0.68 * (x - 0.46)
χ = 0.0817
Aged solar reflectance
Initial solar reflectance

CRRC1 EPA1

(g)

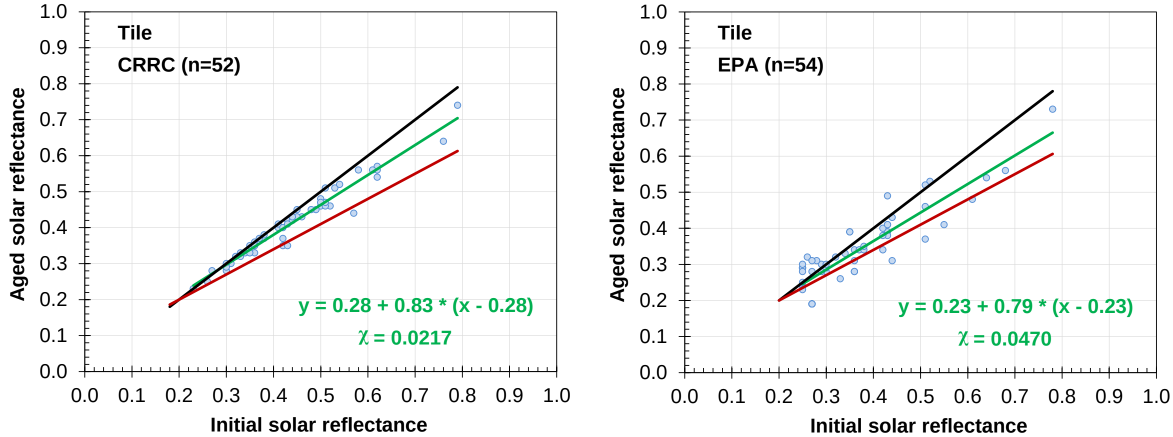


Figure 6. Correlations within each edited database (CRRC1 and EPA1) between the aged solar reflectance (ρ_a) and initial solar reflectance (ρ_i) of (a) factory-applied coating, (b) field-applied coating, (c) metal, (d) modified bitumen, (e) shingle, (f) single-ply membrane and (g) tile products. The green line and corresponding equation show the best unconstrained linear fit and its root mean square error χ; the red line represents 2008 Title 24 provisional aged solar reflectance $\rho'_{a,T24}$; and the black line marks no change ($\rho_a = \rho_i$).

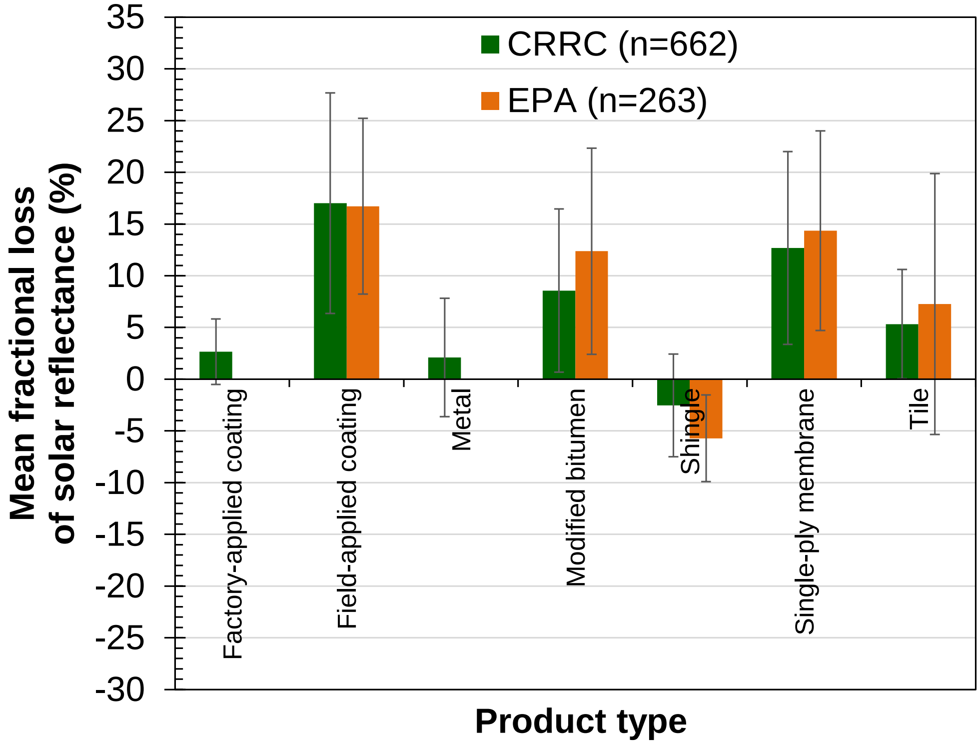
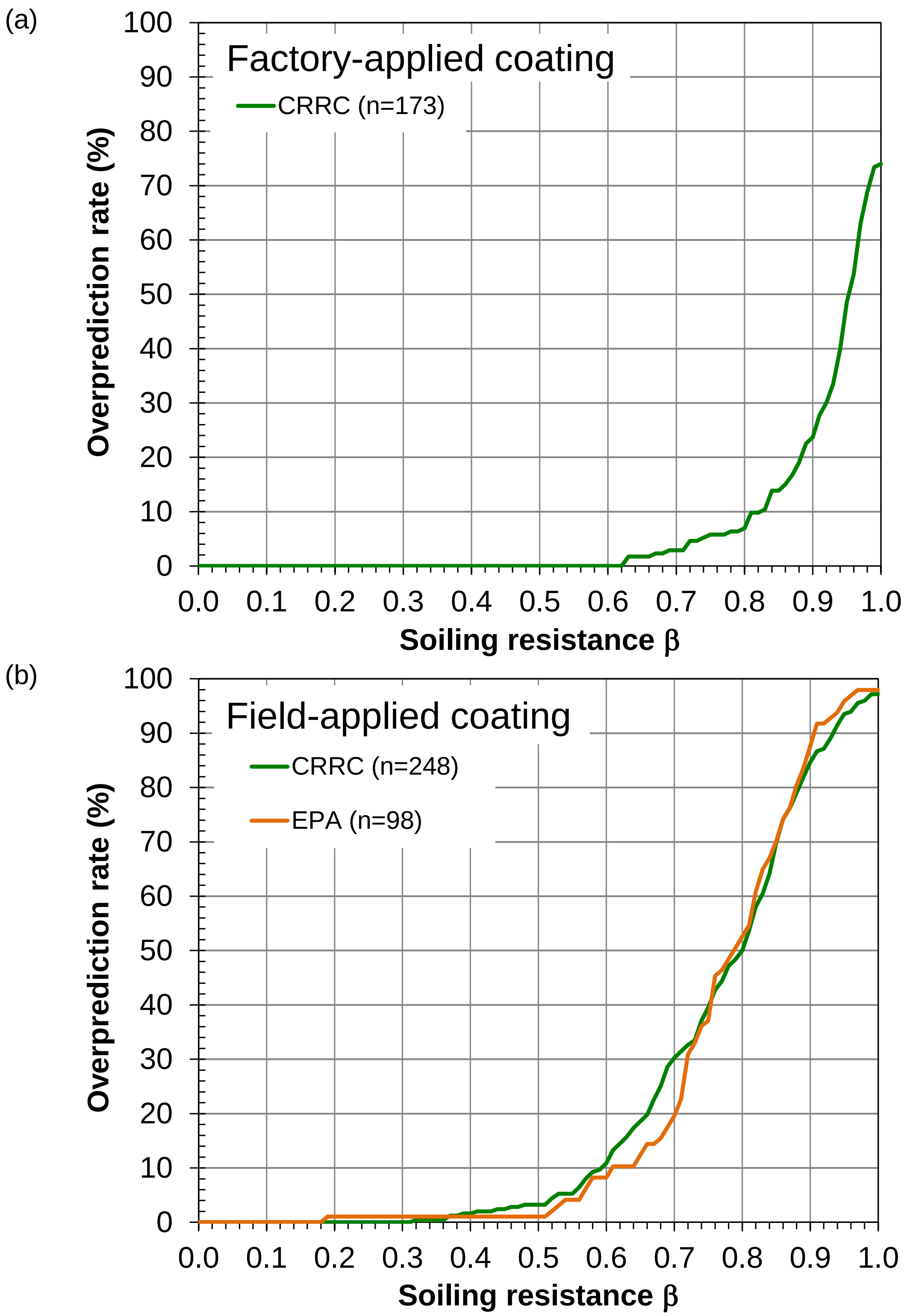
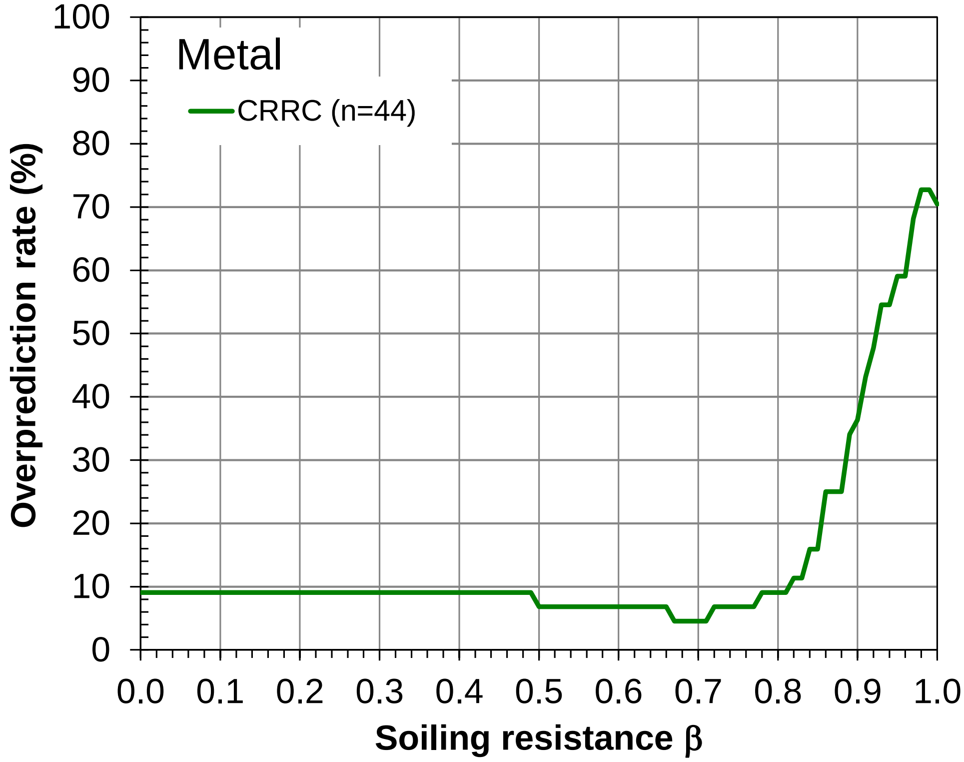


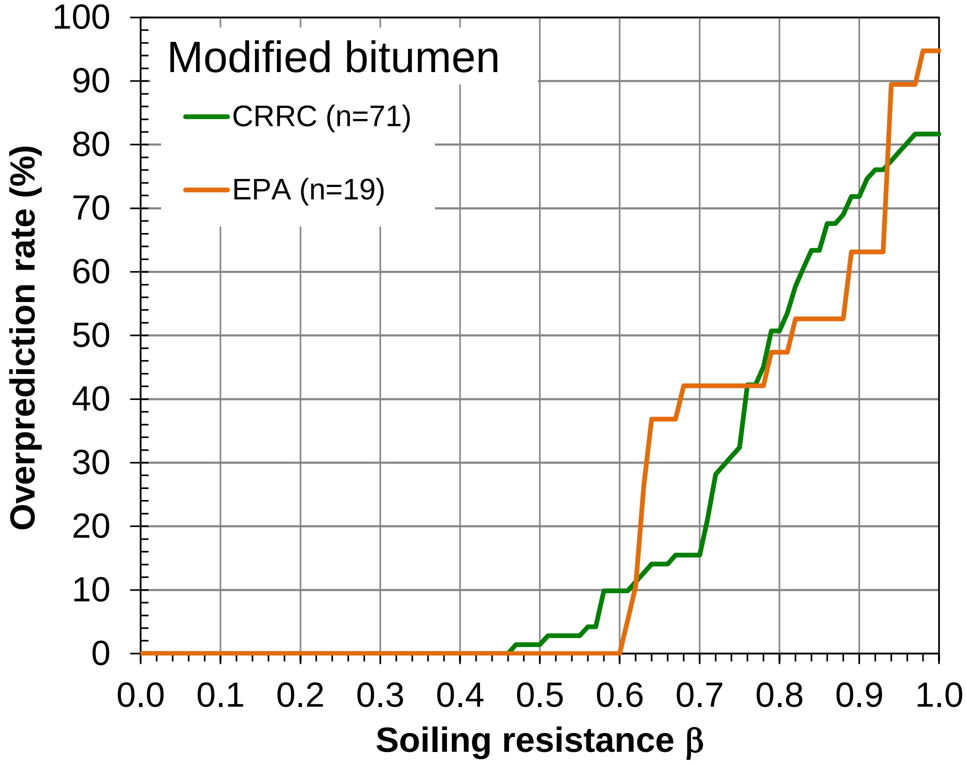
Figure 7. Mean fractional loss of solar reflectance ϕ by product type in the CRRC1 and EPA1 edited databases. Error bars mark one standard deviation.


(a)
Factory-applied coating
CRRC (n=173)
Overprediction rate (%)
Soiling resistance β
0 10 20 30 40 50 60 70 80 90 100
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
(b)
Field-applied coating
CRRC (n=248)
EPA (n=98)
Overprediction rate (%)
Soiling resistance β
0 10 20 30 40 50 60 70 80 90 100
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

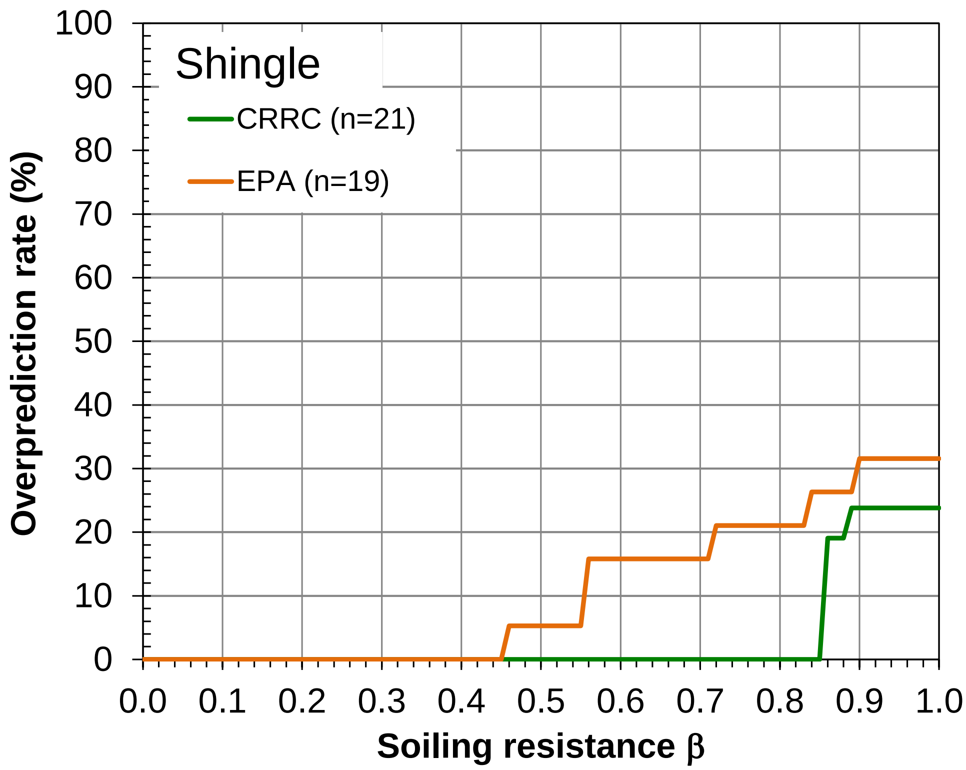
(c)


Metal
CRRC (n=44)
Overprediction rate (%)
Soiling resistance β
0
10
20
30
40
50
60
70
80
90
100
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

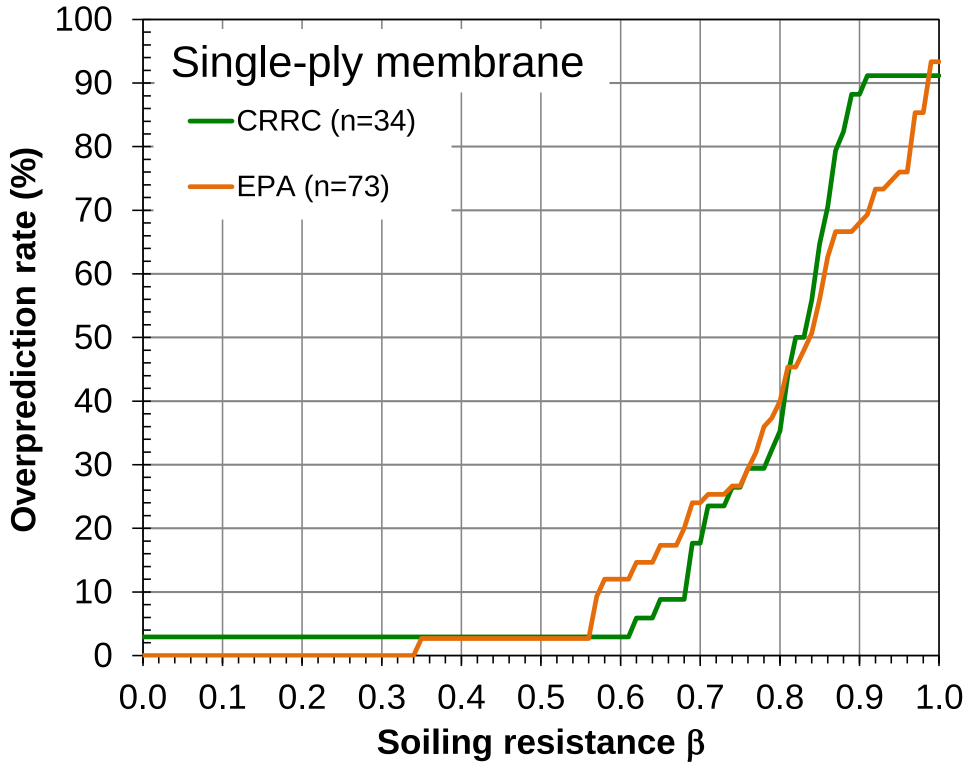
(d)


Modified bitumen
CRRC (n=71)
EPA (n=19)
Overprediction rate (%)
Soiling resistance β
0
10
20
30
40
50
60
70
80
90
100
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

(e)


Shingle
CRRC (n=21)
EPA (n=19)
Overprediction rate (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Soiling resistance β

(f)


Single-ply membrane
CRRC (n=34)
EPA (n=73)
Overprediction rate (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Soiling resistance β

(g)

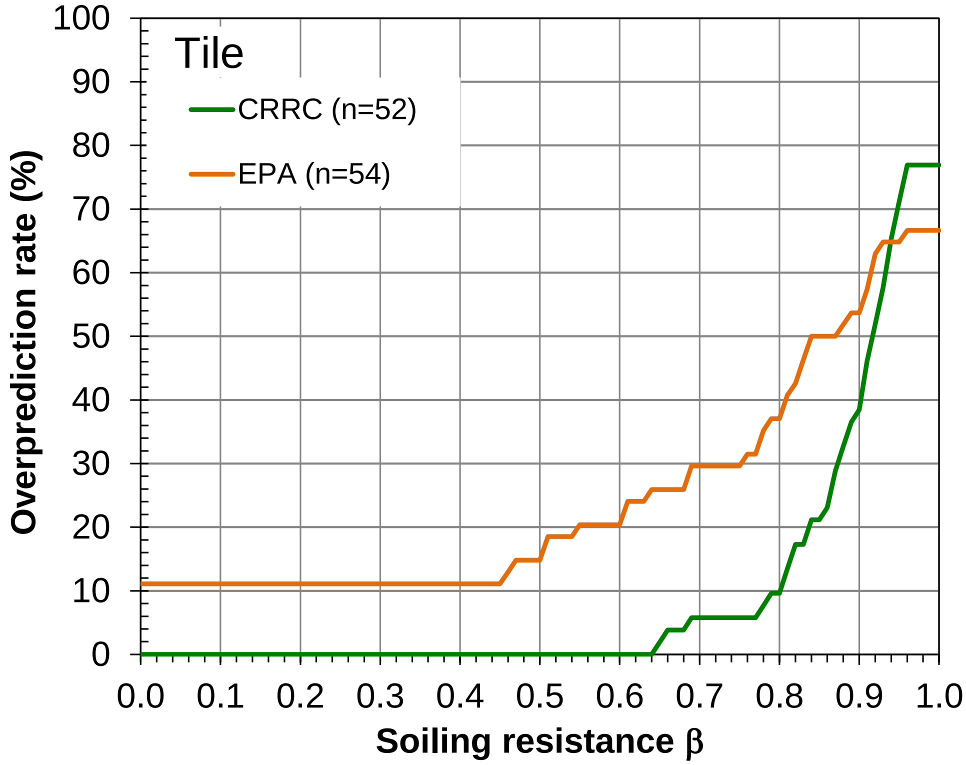


Figure 8. Overprediction rate vs. soiling resistance β by product type and database (CRRC1 and EPA1), shown for (a) factory-applied coating, (b) field-applied coating, (c) metal, (d) modified bitumen, (e) shingle, (f) shingle-ply membrane, and (g) tile. All values computed with common soil layer solar reflectance $\alpha_0 = 0.20$.